様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Dense 3-axis tactile sensing and AI to implement human-like manual skills in robots

研究課題名（英文）Dense 3-axis tactile sensing and AI to implement human-like manual skills in robots

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交付決定額（研究期間全体）：（直接経費）　13,400,000円

研究成果の概要（和文）：触覚センサーをさらに進化させました。368個の3軸触覚センサーがロボットハンドを覆います。さらに、ロボットハンドの掌側を厚い皮膚でほぼ完全に覆うことができるように、ロボットハンドをさらに進化させました。また、人間の手の触覚センサーをさらに進化させ、物体と接触する人間の皮膚を覆わずに、指先の接触力に加え、接触位置も測定できるようになりました。さらに、将来的にはロボットの関節などに使用できるよう、伸縮可能なセンサーを開発しました。

さらに、ロボットの手やグリッパーに埋め込んだ触覚センサーを触覚AIに利用しました。

研究成果の学術的意義や社会的意義
Robots in the future are expected to work for and with humans. Tactile sensors are crucial for robots to perform human-like grasping and manipulation. Example applications would be the automation of warehouses, factories and agricultural activities.

研究成果の概要（英文）：We have further developed our tactile sensors. 368 3-axis tactile sensors cover the robot hand. Furthermore, we have further developed a robot hand that allows to cover the palmar side of the robot hand nearly completely with thick skin. We have also further developed the tactile sensors for human hands, which now allow measuring the contact position in addition to the contact force on the fingertip without covering the human skin that is in contact with the object. Furthermore, we have developed sensors that are stretchable, so that they can be used for robot joints for example in the future.

Moreover, we have used the tactile sensors embedded in robot hands and grippers for tactile AI. The robot was able to perform various in-hand manipulations, detect object properties, and predict grasp stability as well as detect slip. We use, implement and improve state of the art machine learning methods such as attention mechanisms, ensemble learning and graph neural networks.

研究分野：Tactile Sensing for Robots

キーワード：Robotics　Tactile Sensing

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

Distributed tactile sensors have been integrated into few robotic hands. A common limitation is that a large number of sensors requires extensive wiring. For example, the Sugano lab has developed the human-symbiotic robot TWENDY-ONE. Each hand has 133 soft 4x4 mm single-axis pressure sensors in the fingertips, and 108 of 7.5x7.5 mm in the rest of the hand. Only the fingertips also include one 6-axis sensor each. Only the transducers are included directly in the fingers, and the hand requires a large amount of wires and voluminous additional electronics. Increasing the number of sensors with this approach is not feasible. Also, most existing tactile sensors are not soft and robust.

Optical sensors (such as Gelsight) can achieve dense 3-axis tactile sensing and have been used for example for texture recognition [1], but such dense optical sensors are thick and have been implemented only in fingertips; as they are bulky, even the integration in fingertips is not possible for many robotic grippers and inhibits many applications. Covering a whole robot with such optical sensors is not feasible.

An increasing, yet still low amount of work uses deep learning for tactile data, mostly convolutional neural networks (CNN), for example with the aforementioned Gelsight sensors [1]. [2] combined the tactile data with visual information, [3] used fingertips with dense distributed pressure sensing to differentiate sliding from slipping, and [4] achieved robust material classification. We believe this is the right direction and should be extended on.

[1] Yuan, et. al. *Active clothing material perception using tactile sensing and deep learning*. IEEE ICRA 2018
[2] Gao, et. al. *Deep learning for tactile understanding from visual and haptic data*. IEEE ICRA 2016
[3] Meier, et. al. *Distinguishing sliding from slipping during object pushing*. IEEE/RSJ IROS 2016
[4] Baishya, et. al. *Robust material classification with a tactile skin using deep learning*. IEEE/RSJ IROS 2016

Problems:

1. **Relying too much on visual data**: Due to a lack of practical tactile sensors, most researchers focus on visual data. However, a sense of touch would be crucial in many scenarios, as it provides the most direct feedback about the contact with the environment, for example for object manipulation and safe human-robot interaction. While currently most AI systems focus on visual data, the addition of reliable tactile data would be a major step towards more autonomous robots, see Fig. 1. The goal of this proposal is to make tactile sensors as robust and easy-to-use as cameras.
2. **Relying on maintenance from human**: Future robots are expected to work without human supervision in extreme and unstructured environments. Robot should be able to repair themselves and be energy independent, etc. We believe that reliable and maintenance-free tactile sensors are a major step towards this goal, as tactile sensors cover the most outer part of robots.
3. **Inferior tactile sensors:** A number of tactile sensors have been developed, but they usually have one or more of the following limitations: excessive wiring, not robust, single sensing modality (typically distributed pressure only), low spatial resolution, sensors only cover some parts of the robot, and they are not soft (important for safe and dexterous manipulation).The integration and maintenance are challenging.
4. **Lack of development on tactile AI**: many machine learning methods have been developed for visual and audio data, but few research has been performed on tactile AI. Adapting

existing algorithms for tactile AI is not trivial, as tactile sensors have different properties, for example convolutional neural networks cannot be easily employed as the shape of distributed tactile sensors is often not rectangular.

２．研究の目的

A sense of touch is crucial for autonomous skills in robots, such as object manipulation and human-robot interaction. Currently, there is a lack of capable, reliable and easily useable tactile sensors. In this proposal we will implement practical tactile sensors that are easy to install and maintain, as well as advanced tactile AI. It is our conviction that an advanced sense of touch (both hardware and software) will be a key-enabler for the next generation of robots with long-term autonomy.

３．研究の方法

We produced advanced tactile sensors and used them for advanced tactile sensing.

４．研究成果

We have further developed our tactile sensors. 368 3-axis tactile sensors cover the robot hand. The sensor are thin, and can therefore cover most of the hands palmar surface, including the finger phalanges and the palm. The sensors have digital output, and therefore only minimal wiring is needed, making the integration in the robot hand feasible without interfering with the dexterity of the hand. The sensors are robust and can therefore be used for long time. The sensors can be calibrated, making it possible to measure for example the weight of the grasped object.

Furthermore, we have further developed a robot hand that allows to cover the palmar side of the robot hand nearly completely with thick skin. We have implemented special joints in order to achieve this.

We have also further developed the tactile sensors for human hands, which now allow measuring the contact position in addition to the contact force on the fingertip without covering the human skin that is in contact with the object. Another version of the sensor can be worn like a fingerhut, which allows to gather more tactile data, albeit of the cost of interfering with the natural interaction of the human with the object.

Furthermore, we have developed sensors that are stretchable, so that they can be used for robot joints for example in the future.

Moreover, we have used the tactile sensors embedded in robot hands and grippers for tactile AI. The robot was able to perform various in-hand manipulations, detect object properties, and predict grasp stability as well as detect slip. We used, implemented and improved state of the art machine learning methods such as attention mechanisms, ensemble learning and graph neural networks. We also use data augmentation for tactile data, which requires different algorithms than vision.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Yan Gang、Schmitz Alexander、Funabashi Satoshi、Somlor Sophon、Tomo Tito Pradhono、Sugano Shigeki	４．巻 1
２．論文標題 A Robotic Grasping State Perception Framework with Multi-Phase Tactile Information and Ensemble Learning	５．発行年 2022年
３．雑誌名 IEEE Robotics and Automation Letters	６．最初と最後の頁 1～1
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LRA.2022.3151260	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Funabashi Satoshi、Isobe Tomoki、Hongyi Fei、Hiramoto Atsumu、Schmitz Alexander、Sugano Shigeki、Ogata Tetsuya	４．巻 7
２．論文標題 Multi-Fingered In-Hand Manipulation With Various Object Properties Using Graph Convolutional Networks and Distributed Tactile Sensors	５．発行年 2022年
３．雑誌名 IEEE Robotics and Automation Letters	６．最初と最後の頁 2102～2109
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LRA.2022.3142417	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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3．学会等名 IEEE/RSJ International Conference on Intelligent Robots and Systems（国際学会）
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

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7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関